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DIGITAL AUDIO BROADCASTING:
The first UK field trial

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Summary

*In February and March of 1990, the BBC was offered equipment for transmission and reception of Digital Audio Broadcasting signals using COFDM (***C***oded* **O***rthogonal* **F***requency* **D***ivision* **M***ultiplex) and MASCAM (***M***asking-pattern* **A***dapted* **S***ub-band* **C***oding* **a***nd* **M***ultiplexing).*

This Report gives details of the trials that were carried out in the London area using a UHF frequency. The conclusions are that the signal is robust in the presence of echoes. As a consequence, COFDM was found to be a suitable modulation system for broadcasting high quality digital sound to the home, to mobile receivers and to portable receivers. The quality of the MASCAM sound signals was very good in the mobile environment.

The signal fails when the signal strength is too low. Thus conventional planning techniques (suitably modified for the different height of the receiving antenna) can be used to identify the service area. Because buildings and hills cast a fairly sharp shadow at UHF, the failure point was usually found to be the point at which line-of-sight propagation to the transmitter was no longer maintained

Additionally it may be concluded that a lower frequency than UHF would be preferable. Higher powers and/or more transmitters, would be needed if UHF is adopted for a service.

The implementation of a co-channel active deflector shows that a single frequency network of transmitters is feasible. However, the problem of ensuring the isolation between the antennas is high enough to prevent distortion or oscillation is not trivial, and may severely restrict the maximum gain of the repeater. In practice the useable gain will depend on the nature of the transmitter site.

Index terms: *Radio broadcasting; digital audio signals; modulation; service area; field tests; frequency; mobile radios; propagation; multipath propagation; echo; planning; radio transmitters*

Issued under the Authority of

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1. INTRODUCTION

Currently, the broadcasting of high quality sound is based on frequency modulation in the VHF bands. The frequency range used in the United Kingdom is 88-105 MHz, expanding to 87.5-108 MHz over the next few years. VHF-FM radio was introduced into Europe in the 1950s and expanded to include stereo operation a decade later. It is still expanding as a high quality broadcasting medium, especially favoured by music lovers.

Unfortunately VHF-FM has been surpassed in quality by recent innovations. Listeners are now able to experience Compact Discs which can provide even higher quality than VHF-FM. High quality is no longer good enough: many listeners want the excellent quality that is now available from CD and R-DAT pre-recorded formats.

The VHF-FM bands are coming under greater pressure and are thus more crowded. This leads to more interference. The VHF-FM service was planned on the basis of reception in the home, using directional antennas at roof-top level to minimise interference. Now, many people wish to receive a signal on a portable receiver, or in a car. Neither of these can be linked easily to an optimum antenna system. Thus their performance is often not as good as may be desired. In practice, reception in cars has many limitations, especially for stereophony, even though the full dynamic range is seldom necessary or desirable.

Thus a new form of transmission which is capable of providing better quality and better spectrum efficiency (i.e. more channels in a given frequency band) would be of great interest.

Within Europe, there are several possible solutions emerging. New modulation techniques are evolving, as are new sound coding techniques. One example is the product of a joint collaborative venture from the Eureka 147 consortium which is studying the possibility of terrestrial Digital Audio Broadcasting (DAB). In particular, the French CCETT* and the German IRT† have produced a system COFDM/MASCAM which can provide high quality broadcasts to mobile receivers as well as to the home and to portable receivers.

The modulation system proposed by the CCETT (**C**oded **O**rthogonal **F**requency **D**ivision **M**ultiplex, COFDM) is a practical member of a whole class of systems which are able to cope with multipath reception by spreading the signal over a wide bandwidth. Despite the 'spreading' it is nevertheless spectrally-efficient because several programmes are transmitted simultaneously, with mathematical orthogonality, within the 'block' of frequency that the technique requires.

The sound coding system proposed by IRT (**M**asking-pattern **A**dapted **S**ub-band **C**oding **a**nd **M**ultiplexing, MASCAM) is an example of one of the sound coding systems developed by the Eureka 147 partners. This particular coding system uses auditory masking to reduce the redundancy in the signal.

The first public demonstration of the COFDM and MASCAM systems was carried out in Geneva in 1988 during the course of an International Telecommunications Union Conference (the WARC-ORB 88 Conference)[1,2,3]. The transmitter was mounted at the TDF transmitting station on Mont Salève. These demonstrations were repeated in 1989 during the course of ITU/COM and CCIR Final Meetings.

As part of the programme of work within the Eureka 147 consortium, the BBC took the initiative to test a COFDM/MASCAM system. This Report describes the field trials and demonstrations that took place.

Whilst this Report describes a system of terrestrial broadcasting, there is a possibility that the system under development could be used in a system of satellite broadcasting[4], or even a hybrid system using both satellites and complementary terrestrial broadcasting[5].

2. BACKGROUND

2.1 The problem in general

As noted in the introduction, VHF-FM provides the main means of supplying high quality sound programmes to the majority of the public, not only in the UK, but also in Europe.

The VHF band provides a useful service. Its propagation characteristics allow good coverage. There is a substantial amount of diffraction of the signals into areas which are not line-of-sight to the transmitter. There is, however, no major interference from the long distance propagation that occurs at the lower frequencies (for example the sporadic-E propagation which is known to affect the quality of television reception in Band I).

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† Institut für Rundfunktechnik

The FM modulation system provides a reasonable spectrum efficiency and good quality output is available. However, the pressure on the use of spectrum is increasing. There are many more prospective operators who wish to start broadcasting, indeed there are pirates who have already commenced. This all leads to an increase in the number of transmissions and an increase in the levels of interference. In many areas the quality of reception is limited by the operation of unauthorised operators, or by the authorisation of more operators than can be accommodated to sensible technical standards.

Whilst the situation in the UK is still relatively satisfactory, there are greater problems on the continent of Europe, where the close packing of channels leads to mutual interference. This also affects reception in the UK, especially around the channel coast.

We are entering a new era in sound quality with the advent of consumer digital recordings on CD and R-DAT format tapes. It is clear that these provide an improved quality for the discerning listener, which cannot be matched by broadcasts using VHF-FM.

2.2 Mobile reception

In the early days of FM broadcasting it was assumed that reception would be in the home with fixed receivers and outdoor antennas. This was a matter of necessity given the fact that receivers were fairly large and used valves, usually powered from mains electricity rather than batteries. Portable VHF receivers were few and far between, and receivers in cars were almost unknown.

Thus the service was largely planned on the basis that the receiver would be in the home. The problems of mobile or portable reception were not addressed at the planning stage. As time went on, the demand for reception with portable receivers and in cars increased. This raised the question of how best to supply a high quality signal to these mobile receivers.

Fixed reception at home is not difficult. Although there are many listeners who use portable receivers indoors, for the best quality reception the signal is received via an outdoor antenna which rejects the main sources of unwanted signal. The transmission standard could be analogue (AM or FM) or digital. Because a fixed outdoor antenna is used, it is possible to use a wide range of digital transmission standards without major difficulty.

If there are unfavourable propagation conditions, such as reflections, these problems can usually be overcome if a suitable antenna is used. There may be interference, but this can also be reduced by using a suitable antenna.

However when the antenna cannot reject the reflected signals arriving from several different directions, there is great potential for distortion. This is the case for reception in vehicles. Car antennas are not usually directional (by design) and will pick up direct and reflected signals without discrimination.

The consequence of receiving a multiplicity of signals is that the signal is distorted. For a channel with multipath propagation, the distortion varies with time. The vehicle may be moving, or other vehicles moving around the receiver give a similar effect. The frequency response of the channel is one of the most familiar measurements. Fig. 1 shows how the frequency response of the channel can be imperfect and vary with both time and position. The frequency response shows that there are bands of frequencies for which the received energy is significantly reduced with small enhancements at other frequencies. These bands vary depending on the position of the receiver and on the position of objects around it.

Simple modulation systems are not tolerant of the selective distortion found in the multipath environment. A digital transmission would normally require good reception of the energy over all its bandwidth. The attenuation of part of the spectrum would distort the signal and in many cases this would lead to failure of reception.

The effect of multipath propagation on FM signals is to reduce the signal level in specific places. This signal reduction often takes the signal level below threshold and so leads to a burst of noise impairing the reception. The same mechanism also leads to distortions such as 's-blasting'.

Work at Research Department has shown that NICAM 728 (a digital transmission system), while rugged enough for television reception where the antennas are usually of good quality, is not suitable for use in a mobile environment. This problem is aggravated if many more channels are needed: as the bandwidth expands there is more potential for distortion.

Thus the problem of multipath propagation requires special techniques to be employed to overcome the distortion that it introduces.

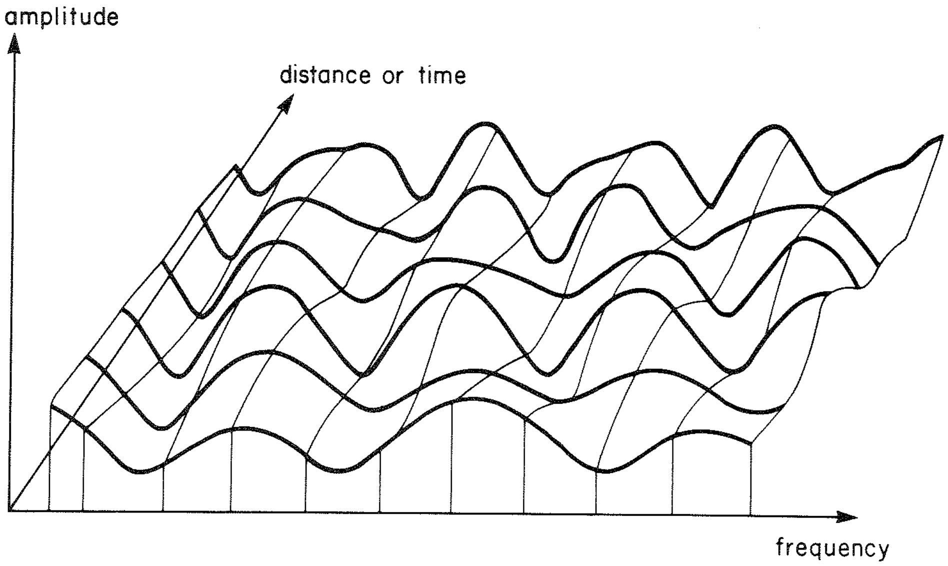


Fig. 1 - The frequency response of a typical channel in the presence of multipath propagation is a function of time and space.

2.3 The desired performance of any new system

We have identified some of the shortcomings of the existing terrestrial broadcasts. If a new system could be introduced, the following features would be desirable.

Digital quality

The signal quality of any new system should at least match the early companded systems such as NICAM. Ideally the quality should match that obtainable from a Compact Disc.

Spectrum efficiency

If a new system is to be broadcast it is necessary to identify a frequency band for it. Given the current shortage of spectrum, it is important that the overall spectral demands should be less than that of an FM broadcast system.

Capacity for market growth

The capacity of the system should be great enough to allow the existing services to transfer to it, and to allow new services to gain access to the spectrum. Current advice suggests that about 10 to 12 channels should be available at the outset. This will provide the public with sufficient incentive to invest in new receivers. We believe that there is potential for growth, with up to 24 channels possibly needed for nationwide services in a mature market.

Reception should be widely available, especially in the home and in vehicles

Although the full quality may be needed only in the quiet conditions found in the home, good quality, uninterrupted, stereo reception is increasingly demanded for reception in cars and on portable receivers. Thus digital quality should be available for all types of reception. Reception should be ubiquitous, and not restricted to areas with good propagation characteristics.

Cost competitive

Since new receivers are required, they must be competitively priced to permit a rapid take-up of the new service.

3. POSSIBLE SOLUTIONS

A European collaborative venture, Eureka Project 147, has been studying several ways of overcoming the problems of Digital Audio Broadcasting.

The Eureka 147/DAB consortium* is a group of companies, broadcasters and research bodies who share a common interest in Digital Audio Broadcasting. They have developed strong links with the European Broadcasting Union and there is strong mutual co-operation.

* The Eureka 147 Partners:

AEG, AG
British Broadcasting Corporation
Bosch-Blaupunkt
CCETT
Deutsche Thompson Brand
Fraunhofer Gesellscaft
Forschunginst. der Deutschen Bundespost
Grundig, AG
Intermetall/ITT
Institut fur Rundfunktechnik
Nederlandse Philips Bedrijven B.V.
La Radiotechnique
Universtat Hannover

The Eureka consortium has terms of reference which refer to terrestrial broadcasting. However there is no reason why the results of the work should not also be used for satellite broadcasting or for a combination of both terrestrial and satellite broadcasting, and this has been recognised within the consortium.

As a result of the collaboration, two key techniques have emerged:

(i) A reliable modulation system for digital RF transmission

(ii) Efficient source coding of high-quality digital audio signals

One of the major developments from within the Eureka 147/DAB group comes from CCETT and IRT. It is called COFDM/MASCAM, and provides an example of the type of system that is now possible.

3.1 Existing standards

There are several digital transmission systems already in use. These systems were developed for specific purposes; in particular they are all designed for static reception and are not tolerant of frequency-selective fading. Although all do the job for which they were intended, they do not provide a solution to this problem.

NICAM

NICAM 728 was developed for use with television. This provides a stereo service to fixed receivers. It is not intended for systems which require more channels, and recent experiments have shown that it is not suitable for uninterrupted reception in cars.

DSR

This is a satellite system which has been deployed in Germany and provides 16 high quality stereo sound signals to fixed receivers. It is not suited to transmitting to mobile receivers because line-of-sight propagation is necessary at 12 GHz and high gain directional antennas are needed to pick up the satellite signals.

MAC/Packet system

This is a European system containing a flexible multiplex capable of providing a wide variety of signals, both sound and television. It is intended for satellite broadcasting to fixed installations and cable TV networks. Again it requires line-of-sight propagation and directional antennas and so is not suitable for reception in vehicles.

3.2 New techniques

3.2.1 Modulation systems

There are many new techniques that are being developed to provide digital transmission for broadcasting. The original problems of multipath propagation are being overcome by various means. Either a modulation system that is tolerant of channel fading is used, or the receiver makes use of diversity reception or equalisation to provide a more tolerant channel. In some cases it is possible to make good use of more than one of these options.

It is interesting that the discussions within the Eureka 147 consortium have shown that it is possible to use these advanced techniques in domestic receivers. The challenge has been to produce the optimum performance at a cost that is acceptable.

Instead of modulating the data onto a single carrier, the COFDM system uses a large number of narrow-band signals each operating at a low data rate[2]. Such a system is called frequency division multiplexing (FDM).

By using narrow-band signals, the carriers are less sensitive to the frequency-selective distortion found in wide-band channels. The bit-rate is low and so the transmission is insensitive to delayed multipath signals. Indeed the delayed signals may provide a useful contribution in many instances. This aspect is enhanced by the introduction of a temporal guard interval. Echoes shorter than the guard interval enhance the received signal. It is only longer echoes that cause degradation of the channel. The choice of the appropriate guard interval is thus an important system parameter.

By using powerful error-protection codes applied in conjunction with powerful receiver techniques (Viterbi or soft-decision maximum likelihood decoding), it is possible to provide a much improved performance.

By using Fast Fourier Transform (FFT) techniques it is possible to use signals with a special mathematical property: orthogonality. This allows us to pack the separate sub-carriers closely together. Even though their spectra are overlapping it is possible to retrieve the transmitted information without interference.

3.2.2 Source coding systems

Associated with the development of the various modulation systems, Eureka 147 has been studying suitable sound coding systems. It is important to try to minimise the bit-rate without compromising the quality of the sound.

Various sound coding techniques have been proposed. The early systems based on companding appear to have less prospects of significant reductions in bit-rate than some of the newer systems based on the discrete cosine transform or sub-band coding.

One of the source coding systems developed within Eureka 147 is the MASCAM system[2], originally proposed by IRT. MASCAM offers high quality audio transmission with a requirement of about 100 kbit/s per monophonic channel. It has since been worked on and improved by several of the collaborators, and in recognition of the changes has been renamed MUSICAM. The MASCAM system was offered to the BBC by IRT to assess the quality of mobile reception at the same time as the trials of COFDM. To avoid confusion, the system used in the trials will be referred to by its historical name, MASCAM. A study of the MASCAM system may be found in Refs. 2 and 6.

By exploiting the psycho-acoustic properties of the human ear the bit-rate can be reduced by a factor of six with respect to that of a Compact Disc while maintaining excellent subjective sound quality. This bit-rate reduction constitutes a major factor in the spectrum efficiency of the DAB approach.

The bit-rate reduction technique is based on an observed property of the ear. If there are loud signals at one or more frequencies they will mask quieter sounds at frequencies close to the louder ones. It is thus possible to economise on the information that is present in the programme without noticeable effect, if the resulting distortion is masked by other components of the signal.

The audio spectrum is divided into a number of sub-bands by a cascade of filters. The filter type allows a simple integrated circuit implementation. Each sub-band is separately quantised, using individual scale factors covering short time blocks.

A feature of this approach is that the energy spectrum of the noise caused by a bit-error is confined to a single sub-band and is limited by that sub-band's scale factor. The error signal thus partially mimics the source signal. In consequence MASCAM has an inherently low sensitivity to transmission errors. The only prerequisite for attaining the highest reproduction quality is that the scale factors (representing some 17% of the useful bit-rate) must be well protected.

4. TRIALS AROUND CRYSTAL PALACE AND CROYDON

As noted in the introduction, the BBC was offered the use of both COFDM and MASCAM equipment for a trial as part of the Eureka 147 programme of work. This offer was accepted and we took the opportunity to assess the performance of the system over typical terrain in the United Kingdom, and to offer demonstrations to some of the interested parties.

The aims of the experiment were to investigate the ruggedness and spectrum efficiency of the system. Thus, in addition to trials of the system from a main transmitter, the experiment also contained an element to show that active deflectors are feasible, thus permitting single-frequency operation.

The key elements of the work were therefore the installation of a main transmitter and active deflector, the survey of the system performance and the demonstrations. This Report gives details of the installation and survey only.

4.1 Site chosen for the main station and frequency of operation

For the first tests it was recognised that an existing broadcast band would have to be used. Bands I and III are not now available for broadcasting in the UK and Band II is occupied by narrow-band systems which do not easily provide space for a COFDM signal of about 7 MHz bandwidth. Thus it was decided that the most convenient band for the first UK trial would be within the UHF television bands.

It was decided that the most suitable transmitter location would be at the Crystal Palace UHF television station in south London, and that the coverage area should be to the south of the transmitter.

Four 1 MW ERP television transmissions are radiated from Crystal Palace in Band IV. Consequently most neighbouring main stations and all Crystal Palace relays operate in Band V, thereby virtually precluding use of any channel within Band V. The tests were therefore carried out within Channel 28, using a centre frequency of 531 MHz. This is mid-way between the co-sited television transmissions on Channels 26 and 30, so particular care had to be taken with regard to filtering at both transmitter and receiver. The maximum radiated power was limited by the need to protect a co-channel and co-polarized television relay at Haslemere, some 60 km to the south-west of Crystal Palace.

The site parameters were as detailed in Table 1.

Table 1

Site:	Crystal Palace
Site Height:	108 m above Ordnance Datum
Antenna Height:	120 m above ground level
Antenna:	Four tiers of vertically polarized log-periodic antennas directed on 180° ETN
Maximum ERP:	140 W
Nominal freq.:	531 MHz

4.2 Equipment used

The equipment used can be divided into two parts, the transmit and the receive side.

4.2.1 Crystal Palace

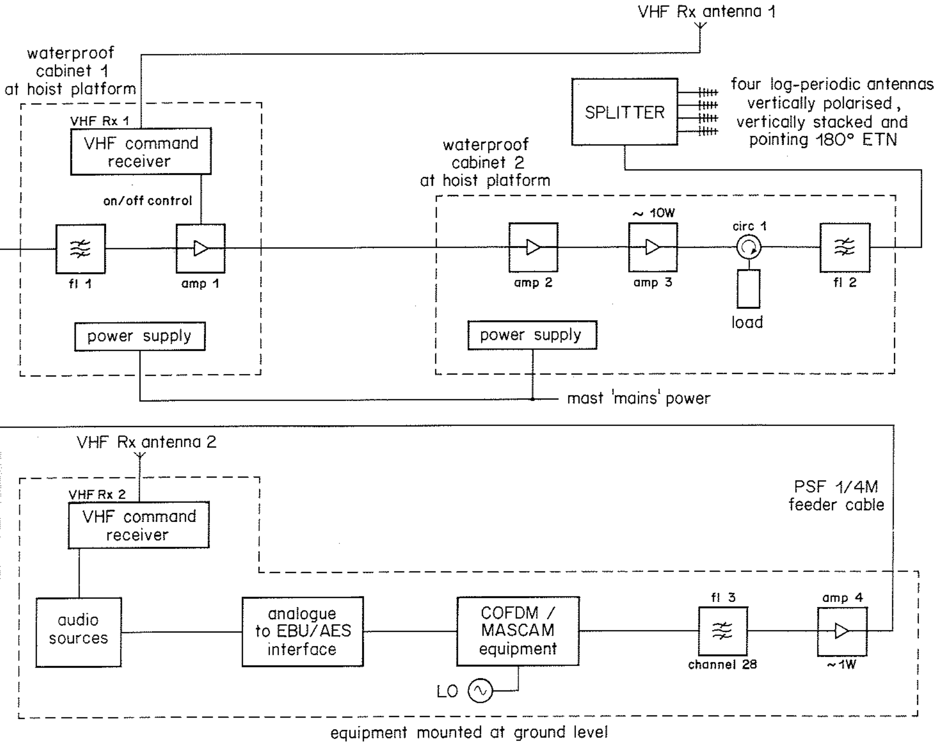
The transmit equipment at Crystal Palace can be conveniently divided into that in the transmitter building at ground level, and the equipment deployed up the mast. The overall arrangement is shown in Fig. 2(a).

The main items in the transmitter hall were:

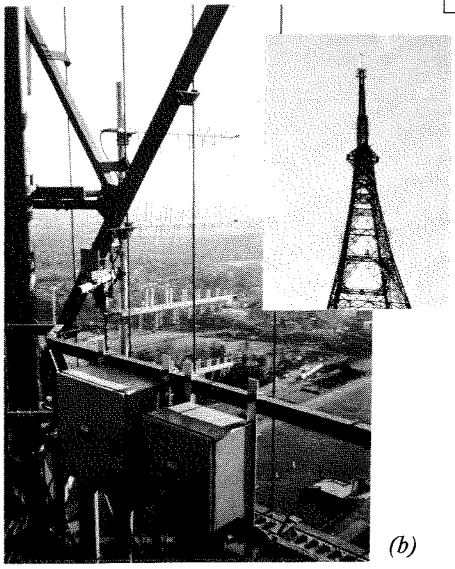
- a CD audio source
- an analogue/EBU-AES interface
- MASCAM source coding equipment
- COFDM modulation equipment
- a frequency up-converter
- low level amplification

This provided a COFDM signal coded with one stereo signal. The other 15 channels were filled with a test signal. The technical details of the transmission are listed in Appendix 1.

The equipment on the mast, Fig. 2(b), was a series of amplifiers to provide the wanted power (10 watts), an array of log-periodic antennas to provide directional signals (thus minimising interference to other television services), and a command receiver for remote control of the system.



(a)



(b)

Fig. 2 - Transmitting equipment.

(a) The arrangement of the equipment at the main Crystal Palace transmitter site.
(b) The transmitting equipment on the mast.

Because the feeder loss was not known accurately, it being too difficult to measure with confidence, a suitable method had to be devised to set the output power and hence the ERP. In view of its location, there would be obvious difficulties in taking a power meter to the output of the final amplifier whenever it was required to calibrate the system.

A 2-tone test was therefore used. The intermodulation-product (IP) level under 2-tone conditions while delivering the required output power was determined in the laboratory.

The level of 2-tone test signal applied to the input of the broadcast chain was then adjusted until the correct IP level was achieved (monitored off-air with a spectrum analyser). This input level was measured using a power meter — easily possible since this point is readily accessible, indoors, at ground level. Attenuation was added to the COFDM signal until it was at this same level.

The radiated spectrum is shown in Fig. 3.

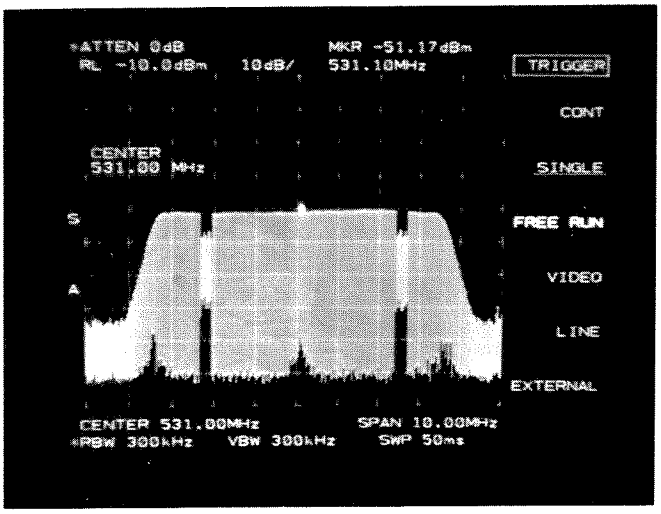


Fig. 3 - The spectrum of the radiated COFDM signal. The spectrum comprises the sine-sweep signal for most of the frame (in this experiment) interspersed with the digital data which occupies about 6% of the multiplex.

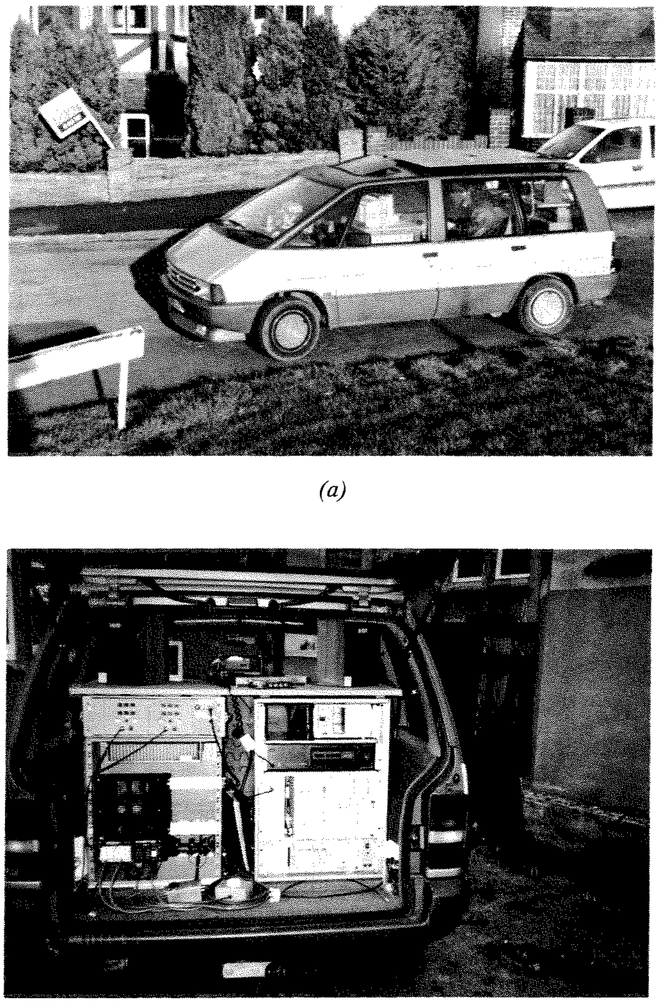
4.2.2 The receiver

The receiving equipment was mounted in a Renault Espace vehicle shown in Fig. 4(a).

The receiving antenna comprised a $\lambda/4$ whip above a metal ground-plane fixed above the car roof. The ground plane was necessary because the vehicle did not possess a metal roof and the laboratory equipment inside the vehicle generated a significant level of RF interference.

In view of the proximity (in frequency and space) of the high-power television transmissions, a band-pass filter was fitted between antenna and receiver. This had an insertion loss of about 2 dB. It being found very useful to have a direct visual display of the received signal, a 3 dB directional coupler, feeding a spectrum analyzer, was also located in the feeder between antenna and receiver input. Although this reduced the overall sensitivity it was considered preferable to leave the coupler in operation throughout the survey.

The COFDM receiver and associated MASCAM decoder were installed in a rack mounted in the rear of the Espace cabin as shown in Fig. 4(b). Since DAB is intended to provide a high quality audio service, the provision of suitable audio amplifiers and loudspeakers was essential. To this end, a good quality amplifier was used along with a small pair of monitoring loudspeakers. To enhance the listening acuity, high quality headphones were also provided.



(a)

(b)

Fig. 4 - The test vehicle.

(a) The vehicle used in the tests.
(b) The equipment in the rear of the test vehicle.

The COFDM equipment available from CCETT transmitted a stereo signal on one of the 16 channels provided within the multiplex. The other 15 channels were coded in such a way that the RF signal was a sine sweep signal. This sweeps over the whole of the channel by radiating all the COFDM carriers with equal amplitude and carefully chosen phases.

The receiver was engineered to perform a Fast Fourier Transform (FFT) of this signal, thus providing an impulse response of the channel. The sine sweep signal could also be viewed directly on an oscilloscope, thus giving a measure of the quality of the channel.

Within the survey vehicle, the results of the FFT were captured using a digital storage oscilloscope. The traces could then be read out via an IEEE interface to a microcomputer, which also recorded the time and allowed the user to categorise the reception area.

One of the main problems of the experiment was to ensure that adequate power supplies were available. Two separate approaches were used: one was to use a high power alternator attached to the vehicle's engine, whilst the other was a separate petrol-driven generator attached on a bracket to the rear of the vehicle. Neither solution was completely satisfactory, but for reasons that are not central to the reported work. It was noted that the ambient electrical noise of the vehicle did degrade the performance of the whole system when compared with laboratory tests by about 2 dB.

4.3 The Kenley Relay

In addition to the main transmitter, an additional relay station was commissioned at Kenley. The valley at Kenley is not served by Crystal Palace because of terrain shielding. However there are places nearby where it may be possible to observe the effects of signals coming from both the main transmitter at Crystal Palace and the relay. This was an important part of the investigation and is discussed in more detail in Section 5.

4.4 Area of operation

The Crystal Palace station is sited near the north end of a ridge of high ground. About 1.5 km south of the station the ground falls by about 60 m to a plain containing the large town of Croydon, part of the conurbation of Greater London. To the south west of Croydon it then rises gradually to a height some 50 - 100 m higher than the transmitter site to an undulating plateau forming the North Downs. Hence over much of this area extending to more than 15 km from Crystal Palace, line-of-sight conditions exist to the DAB transmitting antenna apart from very local building clutter near the receiving terminal.

To the south and south-east of Croydon the topography is much more complex and there are areas less than 10 km from Crystal Palace where substantial terrain shielding occurs.

Fig. 5 shows the areas where mobile reception was unsatisfactory or, in the more general case, completely non-existent. Certain other small areas of unsatisfactory reception were identified, which were too small to indicate on the map; these were mainly at distances greater than 10 km from the transmitter.

In assessing these deficiencies it should be remembered that there was a total of 5 dB attenuation imposed between the receiving antenna and the receiver.

4.5 Survey measurements

The survey involved a series of journeys around the Croydon area, identifying the areas of good and bad reception, and logging the quantitative performance of the channel.

The Croydon conurbation is made up of several distinct types of environment. These were allocated classes as follows:

- dense urban
- urban
- suburban
- rural

The channel impulse response was recorded for each type of environment and the data transferred to a larger computer for analysis.

The impulse response is useful in channel analysis as it allows delayed responses to be identified easily and the delay time can be used to calculate the path difference, and hence to identify the object causing the reflection. Nearby vehicles will cause reflections of the order of 0.2 μs, roadside buildings will cause reflections up to about 0.5 μs and more distant hills and buildings around 8 μs.

The dynamic range of the equipment was about 40 dB. Long delay multipath with amplitude less than this could not be detected. Also, the equipment only operated on signals which arrived within the 16 μs guard interval. Any very long delay multipath would be considered to be part of the next symbol, and therefore appear as a form of aliasing.

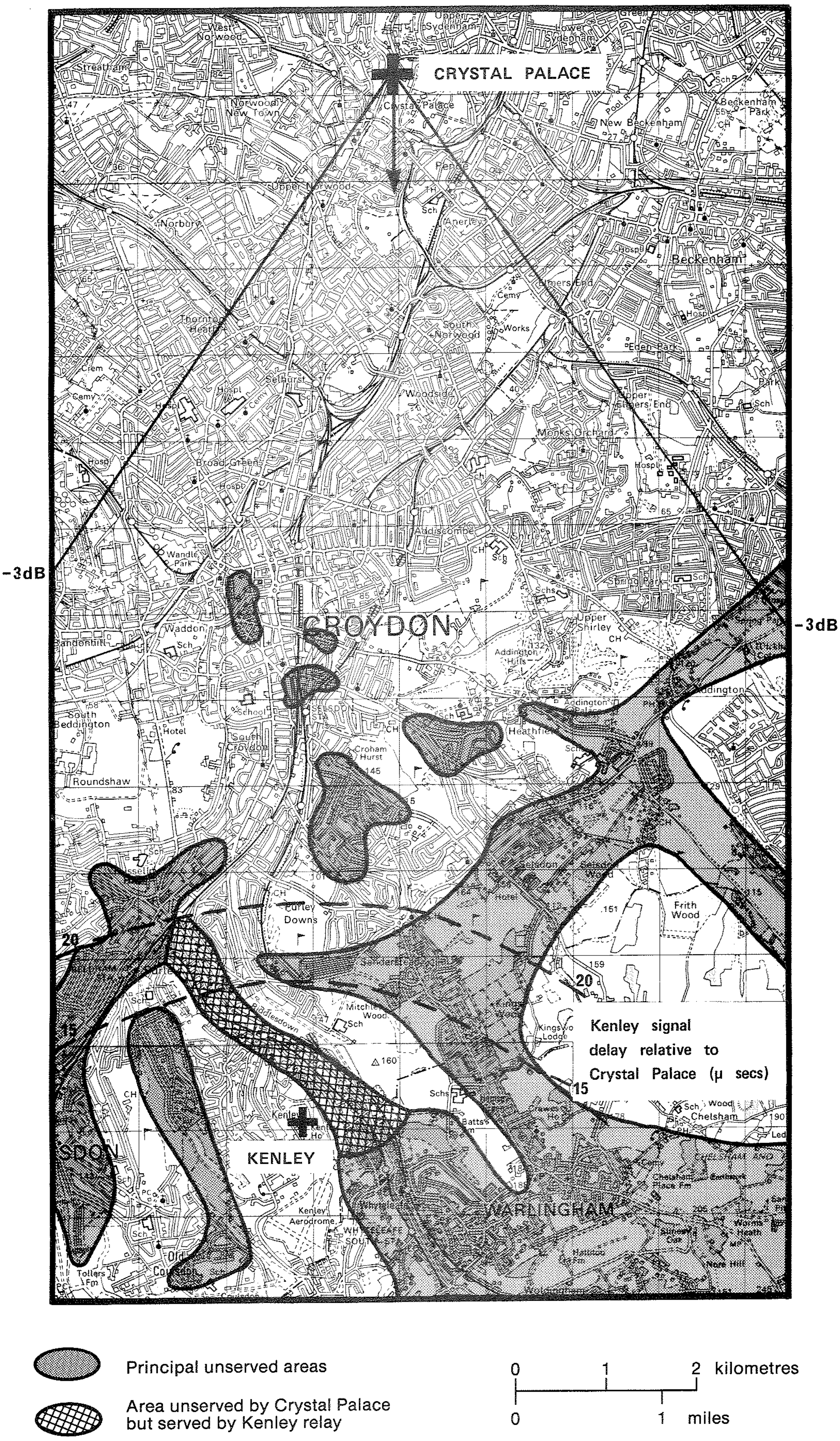

CRYSTAL PALACE
-3dB
-3dB
CROYDON
KENLEY
WARLINGHAM
20
15
20
15
Kenley signal delay relative to Crystal Palace (μ secs)
Principal unserved areas
Area unserved by Crystal Palace but served by Kenley relay
0
1
2 kilometres
0
1 miles

Fig. 5 - Location of Crystal Palace and Kenley transmitter sites, and the coverages obtained.

4.6 Subjective results

The main feature of the survey was that the COFDM system was exceedingly rugged. In general the system worked whenever the field strength was above a certain threshold. Below the threshold the system worked imperfectly, or more usually not at all.

The extent of the service area for the DAB transmissions was established by driving around in the survey vehicle and marking the map wherever the system failed. Failure was judged subjectively by listening to the output of the system. The type of faults heard ranged from a 'gurgling' or 'squeaking' type of sound in the background to harsh pops and squeaks as the system failed. The receiver normally mutes the output to mask the worst of these effects and the level at which this muting occurs could be varied. For the survey the level was set such that the muting did not mask intermittent failures of the system.

For some of the survey work we had, in addition to the MASCAM equipment from IRT, similar equipment made by CCETT. This was a more recent version of the coding system, which included different error-masking features. It was noticeable that there was a difference between the multiplexes in that their muting characteristics were different. This gave a noticeable difference in acceptability at the edge of the service area. Within the service area there was no obvious difference between the bit-rate reduction systems.

Those who heard the mobile demonstration formed the impression that the failure characteristic is important if the system is going to be used near threshold with any regularity. These differences were not readily apparent in the laboratory, where the error-rate in tests tends to be more controlled and less variable. Whilst there was an obvious preference between the two available systems, it is clear that any new developments will have to be tested in the field.

As outlined above, Fig. 5 shows the coverage area of the test transmissions from Crystal Palace. In general, as would be expected for UHF propagation, it was desirable that the receiver was approximately line-of-sight to the transmitter. If there is no direct path but a strong reflected signal the COFDM system continues to provide a service. However, if the signal strength falls, either due to shadowing or because of distance from the transmitter, then the sound decoder begins to fail and the receiver to mute.

It was not a simple task to measure the received signal strength to give quantitative results. The signal bandwidth is much wider than most measuring receivers, and simple power meters were not sufficiently sensitive. Measurements could only be made over a reduced bandwidth and were therefore in error if the channel was subject to fading.

4.7 Objective results

The measurements showed that multipath propagation could be found at high levels in many places. The objective results of the survey can be broken down into types of area.

4.7.1 Dense urban

Dense urban environments give the largest number of reflected paths. These areas are characterised by having a large number of high-rise buildings. Central Croydon and the surrounding town is typical of such an area. Fig. 6(a) shows a typical dense urban location with very severe multipath (near the fly-over in Croydon). The COFDM system makes use of the delayed signals, and the received signal was not noticeably impaired. It can be seen from the channel sounding of Fig. 6(b) that most of the signals arrive within 4 μs of the main signal. This is fairly typical of this sort of environment.

When there was no direct path to the transmitter, the system usually responded to the first reflected signal. Sometimes stronger, but more delayed signals contributed to the received power allowing the system to operate in an extremely adverse location. A typical impulse response is shown in Fig. 6(c).

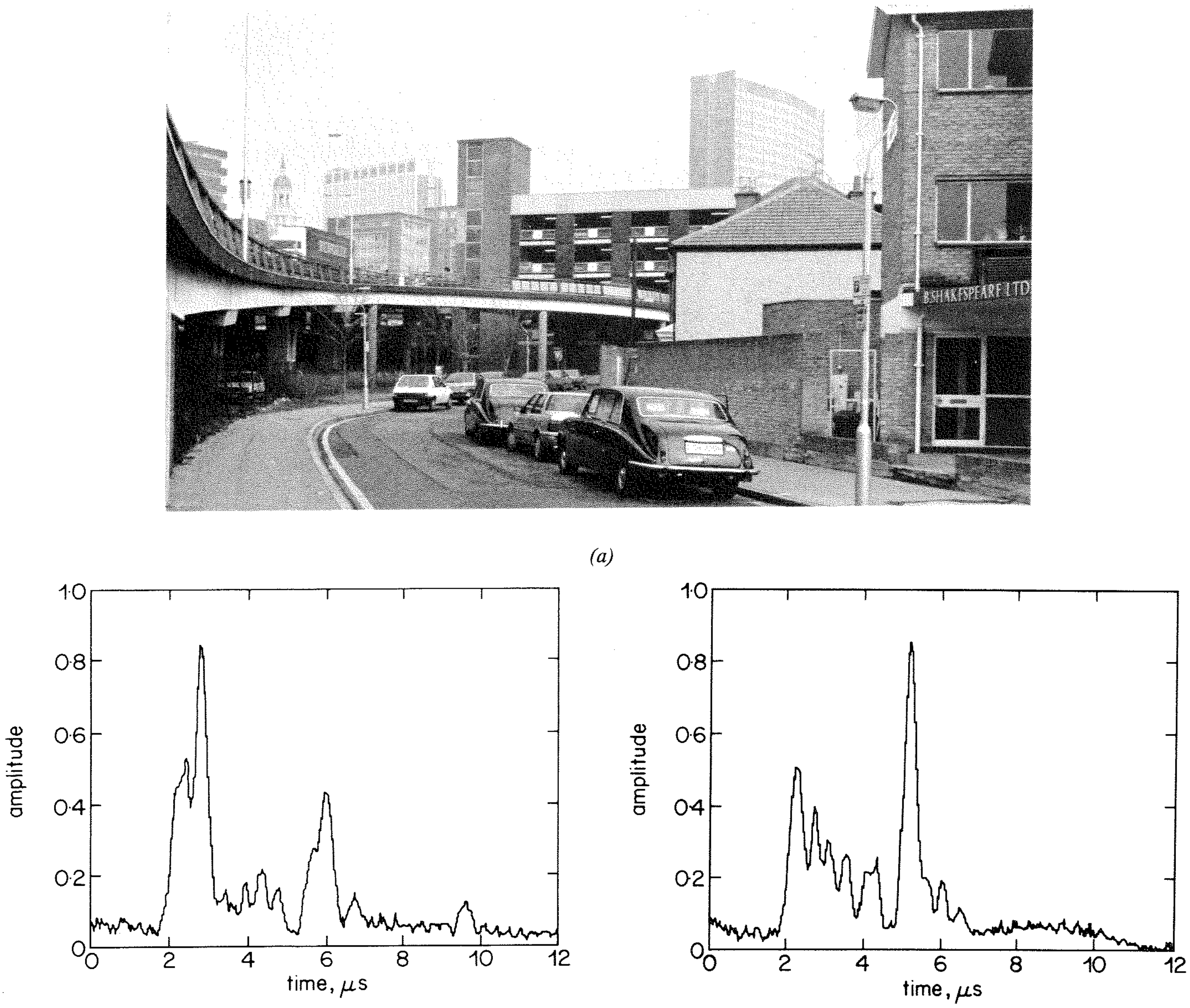
4.7.2 Urban

Fig. 7(a) shows the impulse response of a typical urban environment. The urban recordings were made in the areas around South Croydon and towards Penge and Crystal Palace, where there are many two- and three-storey buildings with no front gardens. There are now less reflected signals than in the dense urban environment. The majority are within 1 to 2 μs of the first.

One very noticeable effect on the impulse response was when a lorry or a bus stopped next to the survey vehicle. Fig. 7(b) shows a typical impulse response with a large amplitude reflection. The reflection is not directly off the vehicle, but is a longer-delay echo, which has gained in importance with the attenuation of the main signal.

4.7.3 Suburban

Much of the housing around the outskirts of Croydon can be classified as suburban, that is predominantly two-storey houses with front gardens. A survey was made in the areas around Purley,



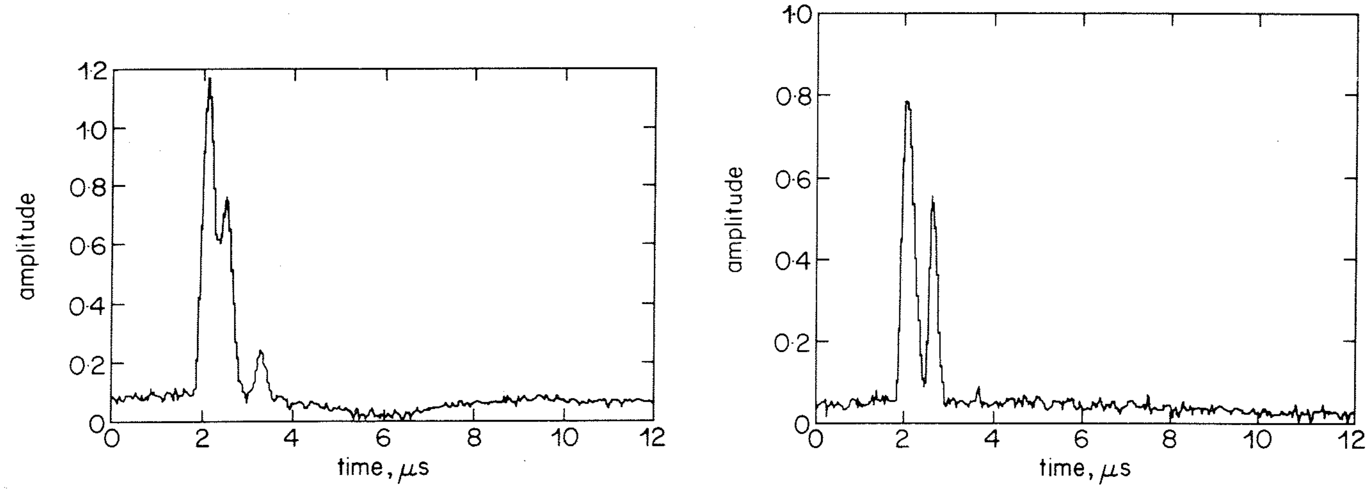
(a)

(b)

(c)

Fig. 6 - Dense urban reception.

(a) A typical dense urban location surveyed during the tests. (b) Channel response in a typical dense urban district.
(c) Channel response in a dense urban district with no direct path to the receiver.

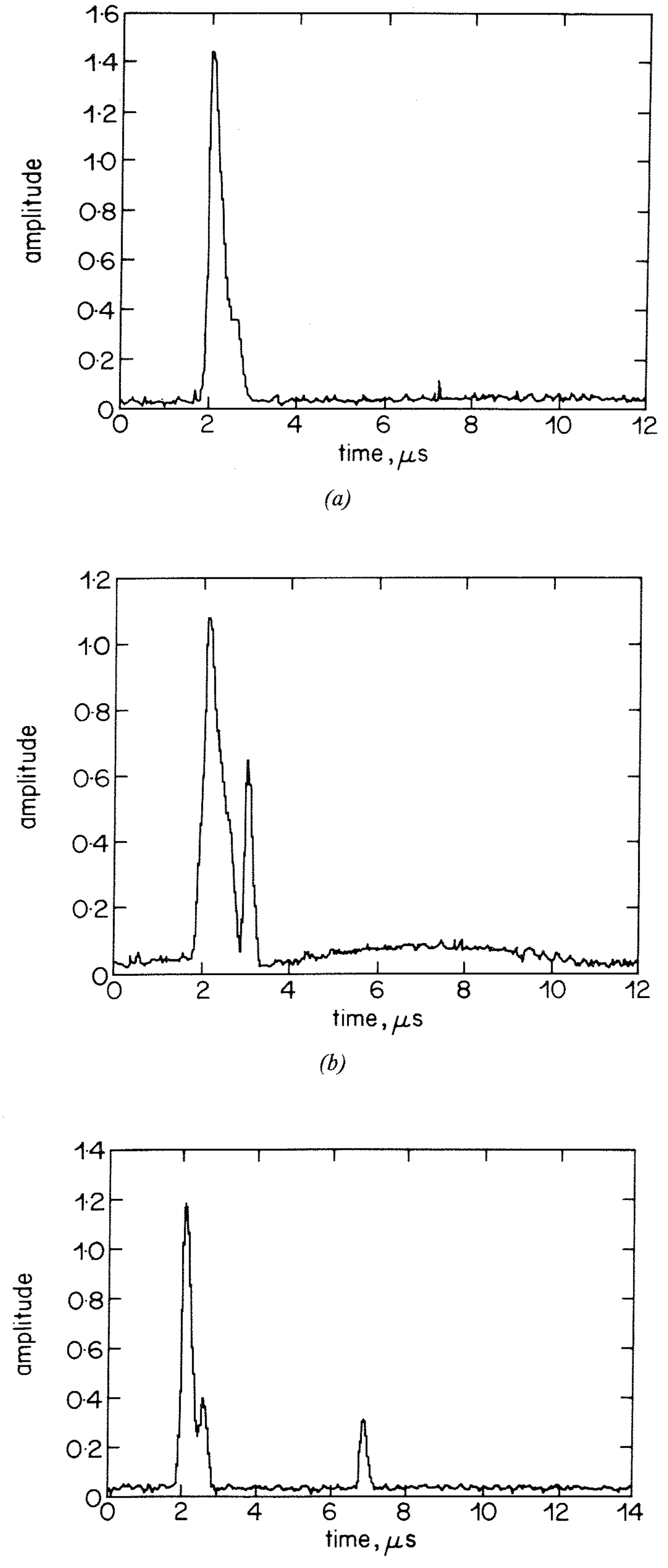


(a)

(b)

Fig. 7 - Urban reception.

(a) Channel response in a typical urban district. (b) Channel response with another vehicle nearby.



(a)

(b)

(c)

Fig. 8 - Suburban reception.

(a) Channel response in a typical suburban district.
(b) Channel response in a typical suburban district with nearby buildings.
(c) An unusual example of long delay echoes in a suburban environment.

Selsdon and Shirley. Fig. 8(a) is a typical impulse response. Significant reflections can occur from nearby buildings as shown in Fig. 8(b). Longer delay signals from more distant buildings can give the most significant reflections but these are relatively rare (see Fig. 8(c)).

4.7.4 Rural

Areas classed as rural (mainly open land) are few and far between around Croydon! Some measurements were made in the neighbourhood of Farleigh and Fickleshole, but these areas are close to the edge of the service area of the system. Fig. 9 shows a typical response, which is fairly clean, with the odd reflection from large buildings.

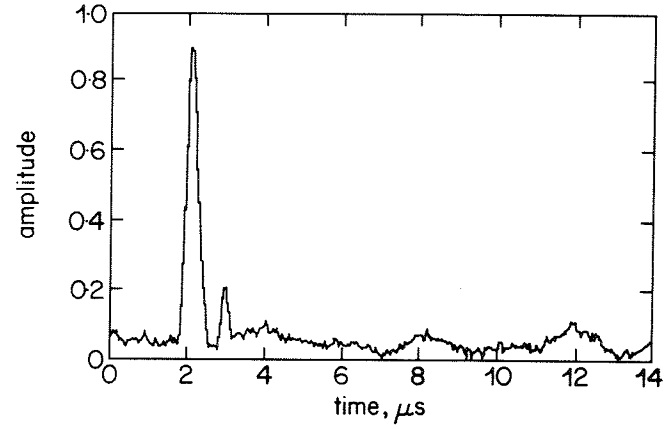


Fig. 9 - Channel response of a typical rural environment.

5. THE USE OF AN ACTIVE DEFLECTOR

5.1 Theory of use

A feature of the COFDM system is the ability to make constructive use of multipath reflections provided that delay times do not exceed a value which is a function of the system design. As a result, co-channel relays can be used. Such relays are often referred to as 'Active Deflectors'. The CCETT has successfully demonstrated the use of two such relays in Rennes.

A primary constraint on the implementation of such relays is the requirement for a high degree of isolation between receiving and transmitting antennas, since this must exceed the overall system gain if the relay is to be stable.

5.2 The Kenley deficiency

It was considered that the existing Kenley TV relay station, some 12 km south of Crystal Palace, represented a suitable location for such a relay. The TV relay serves a narrow but quite deep valley lying approximately transverse to the propagation path from Crystal Palace. The valley was not served by the DAB signal from Crystal Palace.

5.3 The relay

Fig. 5 indicates the relative locations of the Crystal Palace and Kenley sites, together with contours of equal delay of the Kenley signal relative to that from Crystal Palace, taking account of the 4 μs delay within the amplifier at Kenley.

Fig. 10 represents the path profile from Crystal Palace to Kenley and gives an indication of the depth of the valley which the relay is intended to serve.

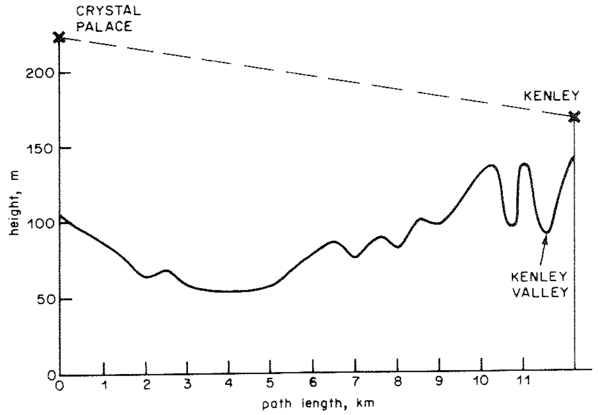


Fig. 10 - The path profile from Crystal Palace to Kenley.

The problem is to achieve sufficient isolation between the receive and transmit antennas to ensure that the repeater is stable. The isolation can be limited by a number of factors which are discussed in detail in Appendix 2. Measurements were made of the isolation and results showed a variation of between 83 dB and 103 dB. This variation was observed to be due to movements of tree branches in the main beam of the antennas. This corresponds to the 'indirect coupling' mechanism discussed in Appendix 2. The site presents a fairly severe challenge in that it is surrounded by trees. Both antennas point across the valley, and are directed towards the facing slope. In achieving these isolation measurements it was necessary to move the receiving antenna to obtain the best compromise between isolation and received field strengths.

Appendix 2 also gives details of a technique for monitoring the stability of the system and hence the margin by which the isolation exceeds the system gain. This method was used to monitor the margin whilst the relay was in use.

The characteristics of the active deflector used were chosen to be:

Receiving antenna:	12-element Yagi, Gain 12 dBd
Receiving antenna bearing:	25° ETN
(N.B. This is not coincident with bearing of Crystal Palace)	
System gain:	82 dB
System delay:	4 μs
Transmitting antenna:	Two tiers of single log-periodics
Transmitting antenna bearing:	North-west
Transmitting antenna gain:	11 dBd
Effective radiated power:	3 W

Fig. 11 shows the Kenley mast and its antennas.

5.4 The result of bringing Kenley on air

The Kenley relay fulfilled coverage expectations by providing a service over that part of the Kenley Valley not served from Crystal Palace. This area is approximately equal to the deficiency in television coverage served by the co-sited UHF television relay, which uses a maximum ERP some 15 dB higher than the DAB active deflector.

From the impulse response it was possible to see whether the receiver was locked to Kenley or to Crystal Palace in areas of coverage overlap. In areas where both transmitters contributed to the overall signal, the transition from one signal being dominant to the other dominating occurred smoothly without any audible effects. The expected hysteresis effect was observed, with the point of transfer dependent on the direction of travel.

Fig. 12(a) shows the system locked to the signal from Crystal Palace. The system remains locked as Kenley is approached (Figs. 12(b) to 12(d)), until the signal from Crystal Palace is small (Fig. 12(e)), when the receiver switches to Kenley as the main signal, Fig. 12(f). The signal from Crystal Palace is now not visible because it arrives before the 16 μs guard interval which is used for channel analysis.

An active deflector can create an environment similar to that found when there is severe multipath propagation. Whilst COFDM can cope with signals spaced by less than the guard interval, signals delayed by more than the guard interval can cause signal degradation if they are of significant amplitude (see Section 6.2).

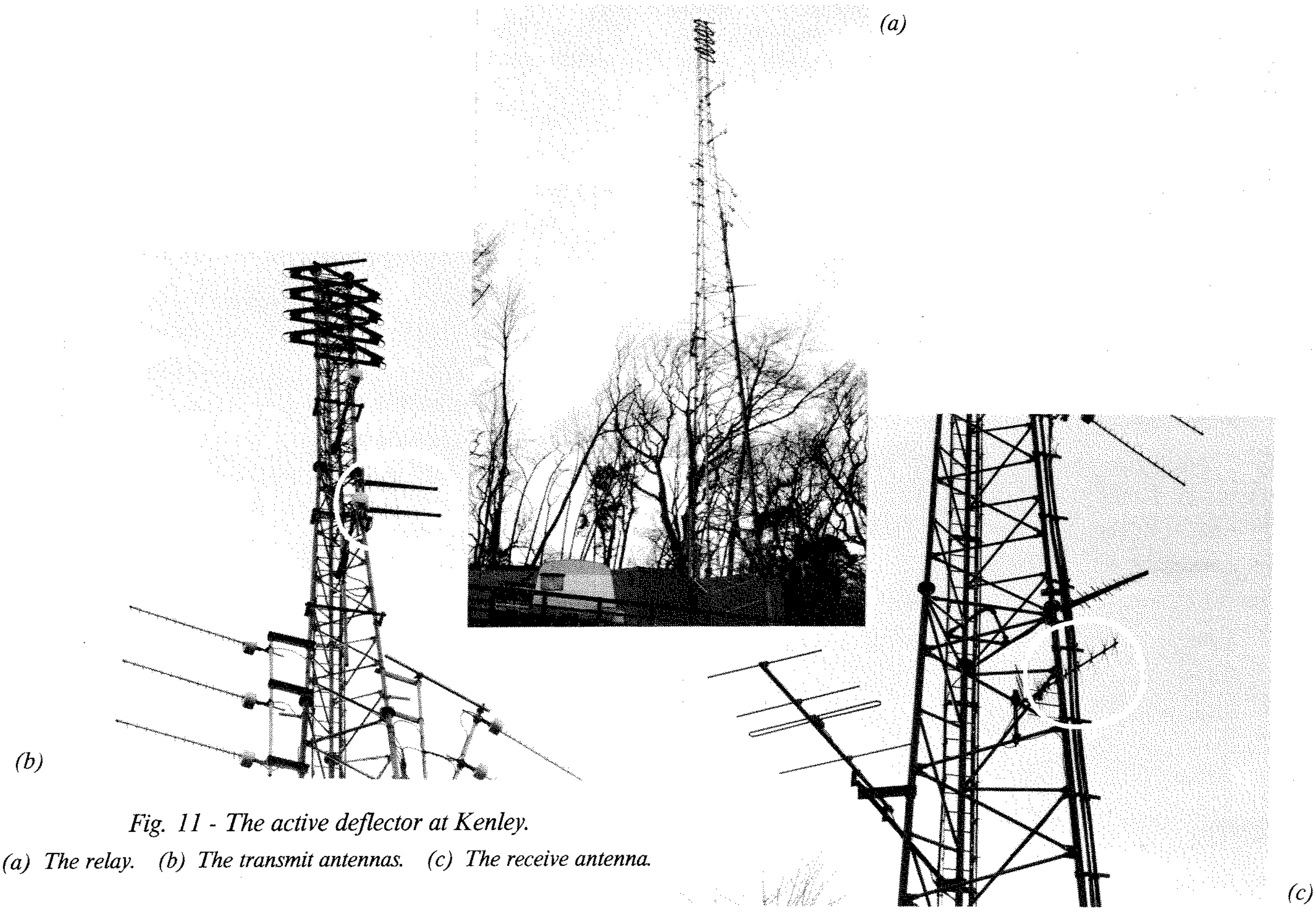


Fig. 11 - The active deflector at Kenley.
(a) The relay. (b) The transmit antennas. (c) The receive antenna.

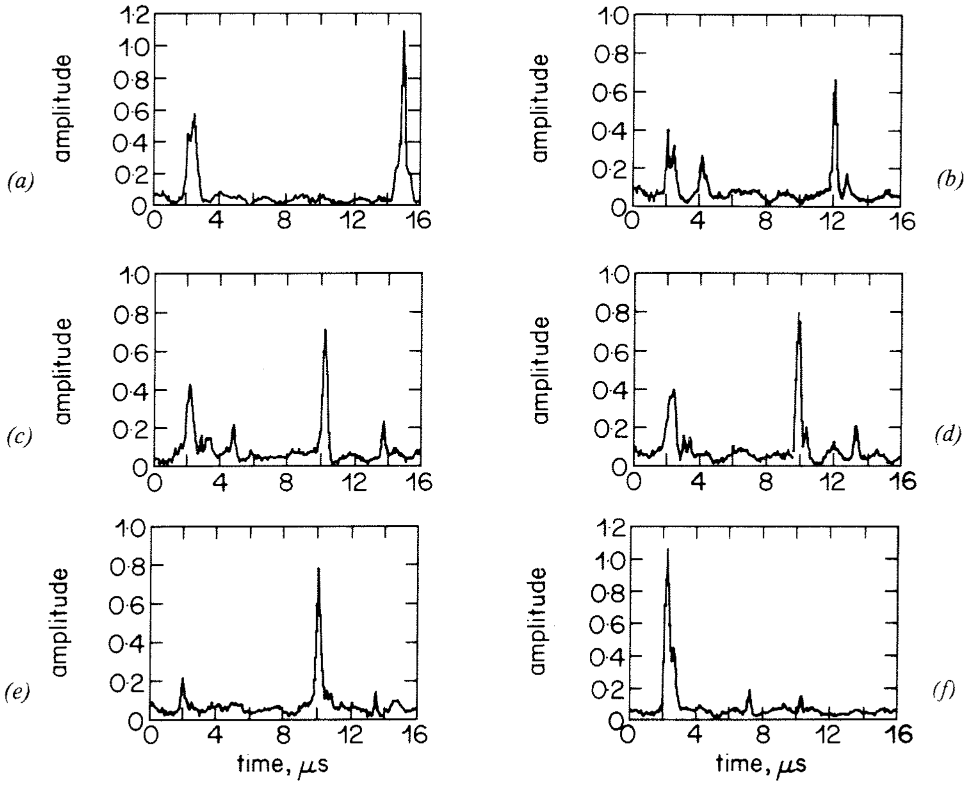


Fig. 12 - Channel response around Kenley.
(a) Some distance from Kenley. (b-d) Approaching Kenley. (e) Crystal Palace signal is weak. (f) Receiver locked to Kenley.

The local topography and the power of the relay did not permit any assessments to be made of system performance in areas where transmissions of both Kenley and Crystal Palace were of comparable magnitude and the time delay of the Kenley signal substantially greater than the guard interval.

6. DISCUSSION

6.1 Service area limits

Reception quality was, in general, uniformly high except close to the coverage limit.

Local variations in signal level were of sufficient magnitude to mask small changes in sensitivity. Thus if a route at the coverage limit was traversed with the receiver attached directly to the antenna, and then again with 3 dB attenuation inserted, little, if any, difference in failure points was observed. Conversely, however, it was found that during static assessments in fringe conditions, reflections from large moving vehicles had a significant effect. These observations confirm that the signal strength can vary rapidly in time and space.

For static reception in an area with little multipath (i.e. a flat frequency response) the reception limit occurred at a receiver input level of about −88 dBm. The tests indicated that a small loss in sensitivity was caused by interference from the vehicle engine and power generator. Since, however, various changes were made to the means of power generation during the tests it was not possible to fully investigate the scope for improvement. It was not judged that any improvement in ignition suppression would be significant in terms of the position of the limit-of-service contour.

With the vehicle moving, a significant hysteresis was observed, in that once the receiver lost lock a higher signal level was then required to re-lock it. Consequently, areas of reception failure could be significantly different when the same road was traversed in different directions.

Adequate, albeit occasionally slightly impaired, reception was obtained in an underpass in the centre of Croydon (at 6 km from the transmitter). The area around this underpass is itself heavily screened by multi-storey office blocks and the route itself is covered for a stretch of about 100 metres. Reception in this difficult environment was seen as a major success of the experiment.

Within the main beam of the transmitting antenna the nearest point to the transmitter at which reception failed was in a low-lying area of Croydon heavily screened by large buildings. In absence of these buildings the area would have been within 'line-of-sight' of the transmitting antenna. This area is also one in which it has been found necessary to provide a UHF television relay (for directional receiving at 10 m above ground level), although in this instance the television relay was needed because of severe multipath problems rather than the lack of field strength.

Virtually all areas which were not within line-of-sight on the basis of terrain path profiles were unserved. When near this line-of-sight limit, performance was critically dependent on local clutter. This superficially pessimistic finding must be judged bearing in mind the fact that the effective radiated power per stereo programme was less than 10 W. However it has obvious implications for the powers of the main stations of such a terrestrial DAB network at UHF and the number of required fill-in relays. If UHF were to be used for this service, the transmit powers would have to be considerably higher than those used in the tests, in order to ensure full coverage in the shadowed areas.

The assumption made in the case of TV planning — that those living in fringe areas will be prepared to make special efforts to receive an adequate signal — is, of course, not valid for car radio reception. Hence, even if it is possible to develop a DAB network in which the coverage of the main stations approximates to that for TV, it seems probable that a greater number of relays would be required to meet the requirements of adequate service to mobile and portable receivers.

6.2 Echoes

The coverage limit appeared to be determined solely by lack of field strength. This result was expected because previous propagation tests carried out from Crystal Palace on the same frequency had indicated an almost complete absence of significant long-delay multipath, and the COFDM system is designed to tolerate, and indeed take advantage of, all signals whose delay is less than a value determined by the system parameters (see Appendix 3). In the current implementation this is about 19 μsec. It was found that the system was capable of operating satisfactorily in multipath conditions causing variations exceeding 20 dB in the RF spectrum.

6.3 Frequency of operation that may be preferred

The clear demonstration that the performance of the system is limited by signal strength means that this is a crucial parameter in the system. Whilst many of the previous worries about multipath propagation have now been overcome, it is still important to ensure that the signal strength is high enough.

To some extent higher power transmitters will overcome this problem, but this is an unsophisticated solution.

Ideally, the frequency of operation should be such that the propagation conditions are favourable. At the lower end of the spectrum, buildings and hills cast less of an RF shadow than at higher frequencies. At UHF there is a strong shadow cast by even modestly sized buildings, and this caused deficiencies in coverage during the experiment. As a consequence, it is strongly advocated that DAB should use the lowest available frequency.

The tests demonstrated a well-known characteristic of digital systems, namely the ability to maintain a high quality of service close to the coverage limit. However, failure, when incurred, tends to be total. This differs markedly from the more graceful degradation at the limit of a conventional FM service, especially when this is assisted by such artifices as automatic transfer from stereo to mono operation in fringe areas. In planning terms this means that much greater attention would require to be paid to determining the precise position of coverage limits because, although degradation of quality over small areas may be acceptable, a complete loss of service is not. This in turn means that the planning of such networks at UHF would be more complex than at VHF because of the greater variability of field strength with location.

For conventional planning, in which overlapping main stations use different frequency blocks (and are not required to carry the same programmes), and relays use *different* blocks from their parent stations, some form of automatic retuning of receivers at coverage limits would seem essential. In the case where relays operate on the *same* frequency block as the parent, as exemplified by the Kenley relay in our experiment, either the planning of such relays will be constrained by the practical limitations of ensuring sufficient isolation, or costs will be increased by the need for separate programme feeds.

6.4 Spectrum efficiency considerations

The spectrum efficiency of a COFDM system with parameters outlined in Appendix 1 is about 0.8 bit/Hz if we consider a single channel. Before we can compare this with other transmission standards it is useful to consider the spectral allocation required in order to provide all countries with one programme. This requires knowledge of the spectrum required for a single channel in isolation, and the frequency re-use that is possible in a world-wide plan.

As currently implemented in the equipment tested by CCETT, the COFDM system is designed to carry 16 stereo programmes plus a data channel in an overall bandwidth of about 8 MHz. Current studies suggest that further developments may permit between 12 and 16 stereo programmes in a 4 MHz block. This is equivalent to a range between 0.25 MHz/stereo programme and about 0.5 MHz/stereo programme before we consider the frequency re-use factor.

If a smaller number of programmes were to be accepted then the block size could be reduced *pro rata*. However, field trials would be necessary to ensure that sufficient independence between the fading of individual COFDM carriers is maintained at any smaller block width. This question is of crucial importance and it is hoped to investigate it further.

There are two conditions for the planning of a DAB network for which spectrum utilization comparisons may be made with other networks. These are:

(i) Conventional planning in which overlapping stations use different frequency blocks. A detailed study of this requires a number of assumptions to be made about propagation characteristics and the minimum acceptable wanted-to-interfering-signal ratio. However the minimum possible value is readily established knowing that this ratio is positive and that co-channel stations therefore cannot have overlapping coverages. A hexagonal lattice requiring a minimum of seven frequency blocks can then be conjectured. More realistically, a number in excess of ten would be needed, leading to a frequency utilization factor similar to that for FM. Such a network is, however, capable of being extended indefinitely without any requirement for overlapping stations to carry the same programme.

(ii) Use of the Single Frequency Network (SFN) concept, as exemplified by the Kenley relay, but extended to cover a whole national network. Subject to the constraints on applicability of such a network discussed below, the same frequency block can be used throughout the full extent of any area requiring the same set of programmes, thereby achieving the utilization factor of 3 - 4 programmes/MHz within this area. However if individual national or regional requirements are different, then different frequency blocks must be used in adjoining areas. Assuming all countries in

Europe and North Africa require different programmes from their neighbours then, with a few exceptions, it would be possible to envisage use of three frequency blocks arranged to ensure that different blocks are used in adjoining countries. By the map-colouring theorem, four frequency blocks should be adequate to facilitate separate SFNs in every country.

This leads to a minimum overall spectrum requirement of between 0.75 and 1.5 MHz/stereo programme to provide a world-wide service.

Usage of Band II for FM services gives a useful comparison to the above values of 3 to 4 programmes/MHz. Planning studies carried out in preparation for the 1984 Region 1 VHF/FM Conference, subsequently included in CCIR Report 944[7], indicated that for 100% coverage of an extended area, a minimum of 3.1 MHz per stereo programme network is required. Within the UK and Eire only 2.2 MHz is available for each national network. However this reduction from the theoretical is feasible only because of the absence of land boundaries with other countries, and in recognition of the fact that 100% area coverage is not achieved.

No formal planning has been carried out for a conventional digital system such as NICAM. To provide a service in a hexagonal lattice would require a minimum of 3.4 MHz/programme. In practice this is highly optimistic and a figure closer to 10 MHz/stereo programme would be more appropriate. Thus the SFN approach using COFDM offers significant economies in spectrum.

6.5 Relays

The Kenley Relay clearly showed that the use of active deflectors can fill a deficiency. Thus, provided transmitters are spaced within the constraints of the guard interval, a single frequency network should be feasible.

However, the main message from the experiment is confirmation that it is not easy to engineer an active deflector. Whilst the Kenley relay was successful, it was clear that this site was not particularly suitable. Other sites may be unsatisfactory. If the frequency of operation is different, the isolation obtained may be insufficient to employ an active deflector. This is one factor to be considered in the otherwise strong recommendation that a VHF frequency be employed.

6.6 Planning constraints on a single frequency network

As previously discussed, the ability to re-use the same frequency block, either to fill a ‘hole’ or extend coverage, results from the fact that the system is designed to make constructive use of delayed signals. This results from the incorporation of ‘guard intervals’ between successive symbol periods. As currently implemented, the overall symbol period is 80 μsec of which 16 μsec is occupied by the guard interval.

All delayed signals combine constructively provided the delay is less than the guard interval. As delay times increase, the additive contribution decreases and destructive inter-symbol interference increases until, at a delay time of about twice the guard interval, this destructive interference predominates.

An important element in planning is thus to ensure that the guard interval is sufficiently long to accommodate signals received from neighbouring and, in the case of abnormal propagation, more distant transmitters.

In the case of low-power relays, the required condition can be satisfied by quite short guard intervals. However in the case of mutual interference between main stations much greater delay times are involved and the symbol period and guard interval must be increased accordingly.

Initial studies of the relationship between separation distances and required guard intervals, have shown that for transmitter spacings typical of those between main stations in a UHF TV network, a suitable guard interval has to be of the order of 0.25 ms. There are some differences in the spacings adopted internationally, and so this figure is not precise.

However, another requirement for satisfactory reception in moving vehicles is that received signal characteristics should remain sensibly constant during the duration of the active symbol period[8]. The higher the frequency and the speed of the vehicle, the less likely it becomes that this condition will be satisfied.

Thus an appropriate balance must be struck between transmitter spacings, frequency, and maximum vehicle speed for which the network is to be planned. The first two of these parameters are already linked, in that propagation factors dictate a denser transmitter network with increasing frequency. Possibly a tenuous inverse relationship also holds between transmitter spacing and vehicle speed, in that the former tends to be positively correlated with population density, whereas vehicle speeds are likely to be greater in areas of thin population.

From the above it would seem that UHF bands are less suitable for the SFN concept than VHF.

Adoption of the SFN principle for a terrestrial DAB network will, of course, present certain problems of programme distribution throughout the network because of the need for synchronization. Satellite distribution may afford a good solution.

7. CONCLUSIONS AND RECOMMENDATIONS

COFDM is a modulation system which provides a means of conveying digital information over a path which is subject to echoes and fading. The survey confirmed the ruggedness of operation of the COFDM system and its suitability for reception in cars and other mobile applications. The ultimate limit of operation is, with a COFDM system of 7 MHz bandwidth, dictated by the field strength and not by multipath propagation.

The experiments reported here were carried out at 531 MHz. As a consequence the edge of service area was often limited by shadowing of the ground by buildings or terrain. It is recommended that lower frequencies be tested to see whether an improvement in the shadowing can be achieved without the need for significant increases in transmit power or transmitter sites. It is also recommended that narrower bandwidth systems be investigated to determine at which point non-selective multipath propagation causes significant degradation.

The MASCAM system provided high quality digital sound signals. It is recommended that the failure and muting characteristics of any improvements to the MUSICAM system be carefully assessed to ensure that they provide an acceptable failure mode at the edge of any service area.

An active deflector was successfully deployed. However, it is not sufficiently easy to engineer adequate isolation into the system to consider that active deflectors are readily usable at all sites. If the frequency of operation is lower, then this problem will increase. This topic needs more careful study.

8. ACKNOWLEDGEMENTS

The authors wish to give their sincerest thanks to the engineers at CCETT and IRT for the assistance and advice that they willingly gave during the experiment. Without this help, the work would have not been so successful.

The BBC also thanks the CCETT and IRT for the loan of the equipment which made these tests possible.

Thanks are also given to our colleagues at Research Department who worked hard to get and keep the 'show on the road', and to colleagues in Transmitter Operations Department for help with the installation at Crystal Palace and Kenley.

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APPENDIX 1

Technical Details of the Systems Tested

COFDM

Total number of carriers processed	512
Total number of transmitted carriers	448
Separation of carriers	15.625 kHz
Total bandwidth of the signal	7.0 MHz
Modulation	QPSK with differential decoding
Symbol period	80 μs, with a 16 μs guard interval
Channel coding	Convolutional with Viterbi maximum likelihood decoding rate 1/2 free distance 10
Total useful bit-rate	5.5 Mbit/s
Spectrum efficiency	About 0.5 MHz average per stereo programme for a single frequency network in isolation.

MASCAM

Bit-rate per mono channel	
total bit stream	168 kbit/s
samples	112 kbit/s
scale factors	24 kbit/s
error protection	32 kbit/s
Number of sub-bands	24
Width of sub-bands	
below 8 kHz	500 Hz
above 8 kHz	1 kHz
Block length	
below 8 kHz	8 ms
above 8 kHz	4 ms
Codewords per block	8 samples
Length of samples	1.56 to 12 bits per sample, depending on the sub-band location

APPENDIX 2

Measurement of the Isolation of an Active Deflector

It is well known that you cannot apply negative feedback to improve the behaviour of an amplifier which has internal delays which are significant compared with 1/(bandwidth). Thus, for example, travelling-wave tube (TWT) amplifiers must be linearised by open-loop methods such as pre-correction. However, even though we do not attempt to apply any deliberate feedback, some may occur inadvertently or inescapably. This Appendix briefly considers the effects such feedback will have and some of the implications for the deployment of 'active deflectors' in Digital Audio Broadcasting.

The problem to be analysed is reduced to a very simple approximate model, as shown in Fig. A2.1.

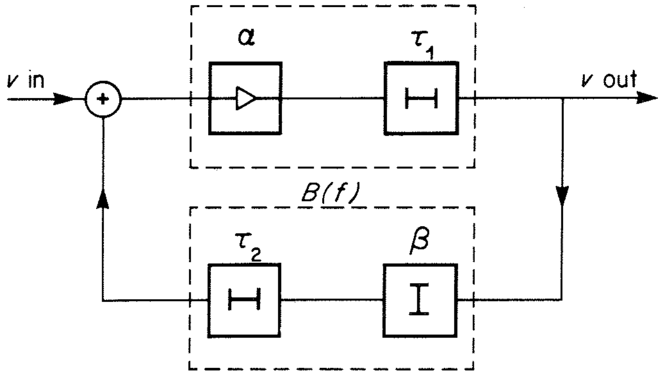

Fig. A2.1 - The simple model of an active deflector with less than perfect isolation.

We assume that an amplifier has been so constructed and aligned as to have flat amplitude/frequency and group-delay/frequency responses, within its intended passband (which is all we shall consider here). We can thus state that its transfer function is a gain constant α and a delay τ_1.

Similarly we suppose an inadvertent feedback path couples a fraction of the output back to the input, where β is the feedback fraction and τ_2 represents any added delay in the feedback path.

If we write $H(f)$ for the overall transfer function we get in our case:

$$H(f) = \frac{\alpha\, e^{-j\omega\tau_1}}{1 - \alpha\beta e^{-j\omega\tau}}$$

where $\tau = \tau_1 + \tau_2$.

The numerator is the normal response of the amplifier, while the denominator term clearly introduces a ripple in the response. The spacing between successive peaks is $\Delta f = 1/\tau$, while the amplitude of the ripple is clearly given by

$$\frac{|H(f)|_{\max}}{|H(f)|_{\min}} = \frac{(1 + \alpha\beta)}{(1 - \alpha\beta)}$$

This simple relationship is illustrated in Figs. A2.2(a) and (b), showing respectively the overall picture and the area of reasonable interest. Of course, oscillation occurs if $\alpha\beta \geq 1$.

A practical system may suffer multiple delayed feedback paths, in which case the analysis becomes more complicated.

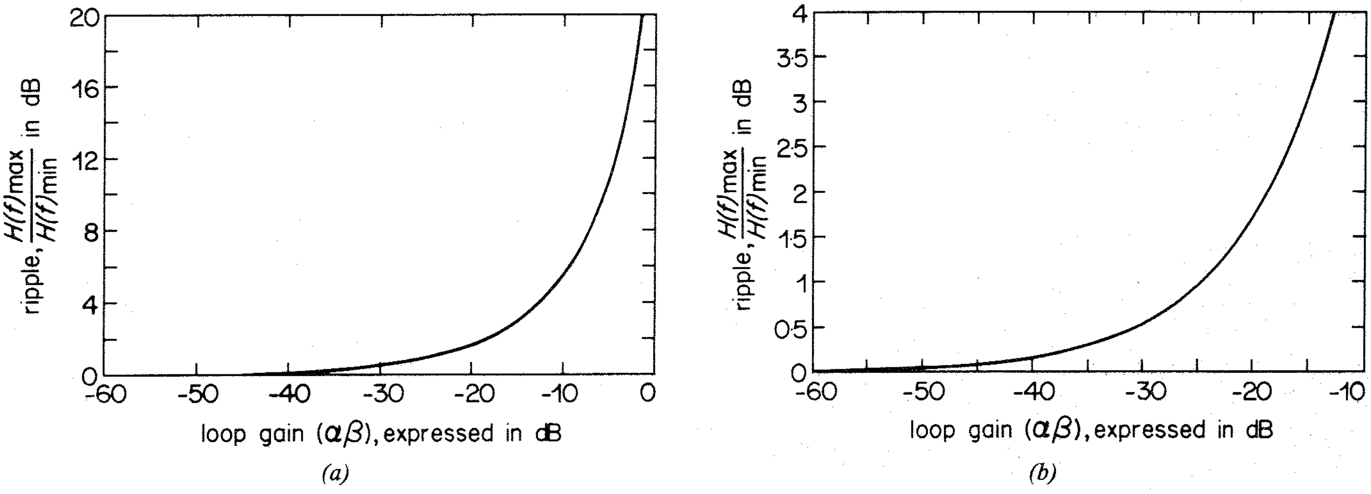

Fig. A2.2 - The ripple in the amplitude/frequency response of the system as a function of the isolation.
(a) Coarse scale. (b) Fine scale.

A repeater constructed during the experiments (see Section 5), received COFDM transmissions of about 7 MHz bandwidth, amplified them and re-transmitted them on the same UHF frequency (about 531 MHz). The equipment used was a standard BBC transposer, modified so as not to transpose, with an (optional) add-on power amplifier. Thus the incoming signal was amplified after down-conversion to an intermediate frequency (IF), but then up-converted again using the same local oscillator before the final stage of power amplification. The IF stage included a SAW filter which contributed a significant proportion of the overall delay through the system. The installation also included directional transmitting and receiving antennas, together with their feeders which, in this temporary arrangement, were relatively lossy.

A repeater system of this type can suffer unintentional feedback from several causes:

(i) Unwanted crosstalk within the repeater assembly itself. This was indeed detectable (as a ripple of a fraction of a dB) with the repeater on the bench driving a dummy load.

(ii) Crosstalk between input and output cables. This proved to be potentially quite serious, but once the need for careful location of the cable runs was recognised this source of crosstalk was reduced sufficiently to be negligible in comparison to other difficulties.

(iii) Direct coupling between the transmit and receive antennas. The installation used a Yagi receiving antenna and a pair of log-periodic antennas for transmitting. They were mounted at different heights on the same mast (vertical separation about 10 m).

(iv) Indirect coupling between the antennas, i.e. reflections from terrain, trees, aircraft, etc. This is a factor which is very difficult to predict.

Initially, direct measurements of isolation were made using a network analyser and used to optimise the location and orientation of the antennas. However, it proved difficult to obtain consistent results. Figures in the range 83 to 103 dB were obtained. (These were measured inclusive of the feeder losses and thus truly represent $1/\beta$ in our simplified model).

The COFDM signal being transmitted in the DAB experiments had a flat spectrum, so monitoring the spectrum of the retransmitted signal for ripple was a very convenient way to judge the isolation and safety margin before oscillation while the repeater was in use.

The isolation was observed to vary in sympathy with the movement of nearby trees in the wind. Thus for this installation indirect coupling between antennas proved to be dominant.

The depth of the ripples in the frequency response obviously depends on the chosen gain α in relation to the instantaneous feedback fraction β. Figs. A2.3 and A2.4 illustrate the transmitted spectrum in two cases. In Fig. A2.3 the gain has been set at a value giving a ripple of the order of 1 dB, which was deemed to be

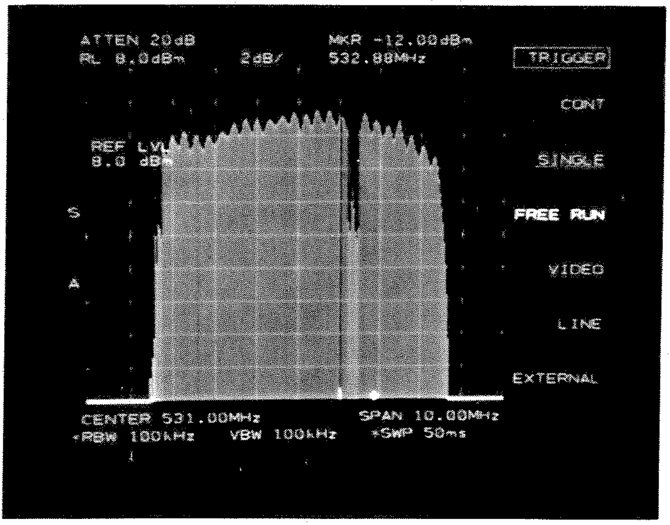

Fig. A2.3 - Spectrum of the radiated signal for a 'reasonable' gain setting.

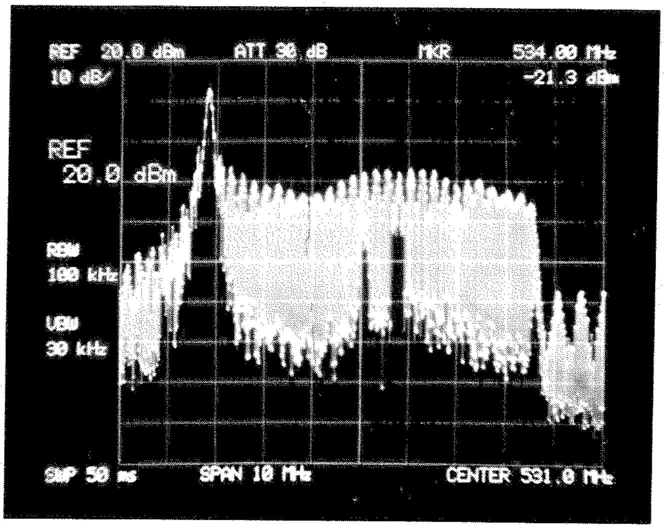

Fig. A2.4 - Spectrum of the 'radiated' signal showing oscillation resulting from excessive gain.

acceptable, while Fig. A2.4 shows a case where oscillation has resulted from the gain being set too high for the prevailing β.

The degree of ripple which is acceptable in this application is not obvious, since COFDM is expressly designed to cope with such frequency-selective impairments introduced by 'natural causes' anyway. In effect we must assign a 'ripple budget' between systematic errors in installations and those resulting from terrain.

The pitch Δf of the ripples in the frequency response was about 250 kHz, implying τ of the order of 4 μs. This agrees with a measurement made using the experimental COFDM equipment itself.

For this installation, the power which could be radiated by the repeater was directly limited by the isolation which could be guaranteed. That the dominant mechanism was reflection from trees implies that planning such repeater installations may not be straightforward. If this behaviour is typical, then prior site tests, at an appropriate season, may be needed for many sites. The BBC would have to be continually aware of construction projects and growth of vegetation in the area.

APPENDIX 3

The Effect of Echoes and Delayed Signals on Reception

In COFDM the period over which the receiver performs correlation is called the *active symbol period* t_S. Since the correlations for all the carriers are performed simultaneously by an FFT (Fast Fourier Transform) process, it is during this period that samples of the received signal are taken and the set then applied to the FFT processor. The results of the FFT are the complex amplitudes (i.e. amplitude and phase) of each of the carriers during the corresponding symbol period. To ensure that orthogonality applies, the frequency spacing of the carriers is chosen to be $1/t_S$.

At the transmitter, coded data are modulated onto each carrier, using differentially-coded QPSK. Thus the transmitted carriers are made to take one of four possible phases, all with the same amplitude, during each transmitted symbol, corresponding to the transmission of two coded bits per symbol. However, the length of the transmitted symbol T_S is not the same as the active symbol period t_S, but rather is extended by a *guard interval* of period Δ, so that $T_S = t_S + \Delta$. The extra period of waveform comprising all the carriers transmitted during the guard interval is transmitted before the active period and is identical to that radiated during the final Δ of the active period; all carriers thus preserve continuity of phase between the guard interval and the active symbol period.

This addition of the guard interval achieves two significant advantages. The first, and perhaps less interesting one, is that the receiver correlation window does not have to be perfectly synchronised to ensure orthogonality. The second advantage is that multipath echoes which arrive no more than Δ later than the first-arriving signal do not cause any intersymbol interference (ISI) at all. ISI in this system would cause a loss of orthogonality (and hence inter-carrier crosstalk) as well as the more obvious crosstalk between symbols on the same carrier. Four cases are illustrated in Figs. A3.1(a) and (b) and Figs. A3.2(a) and (b).

Reception of single path with correct synchronisation:

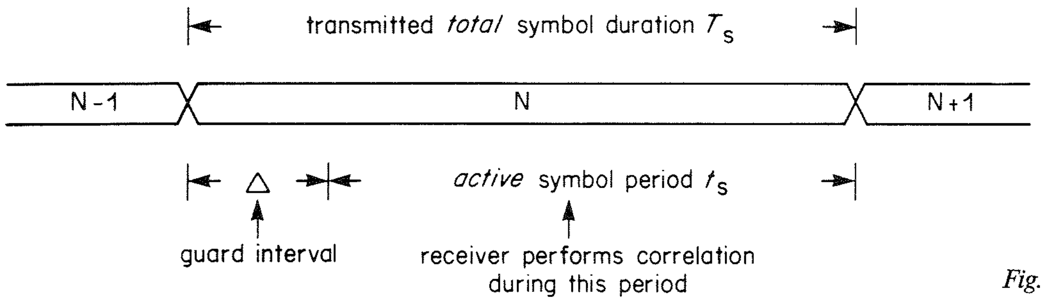
transmitted *total* symbol duration T_S
N-1
N
N+1
Δ
guard interval
active symbol period t_S
receiver performs correlation during this period

Fig. A3.1(a)

Reception of signals delayed by τ, where $\tau < \Delta$:

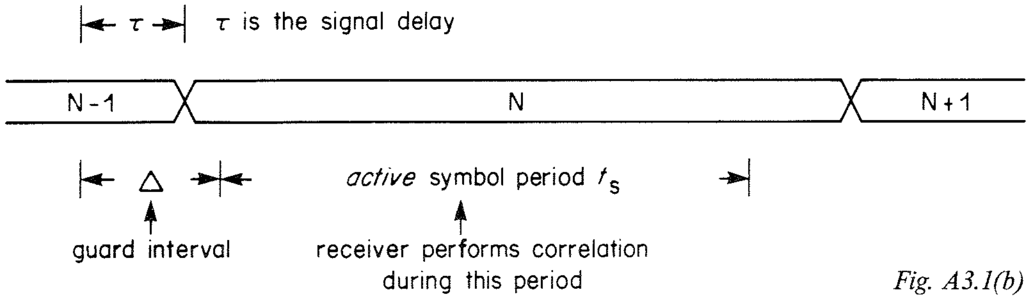
τ
τ is the signal delay
N-1
N
N+1
Δ
guard interval
active symbol period t_S
receiver performs correlation during this period

Fig. A3.1(b)

Clearly, in this case the receiver only 'sees' information pertaining to symbol N, and thus no ISI occurs. Thus this delayed signal is perceived *entirely constructively*, and no diminution of performance occurs.

Reception of signals delayed by τ, where $\tau > T_S$:

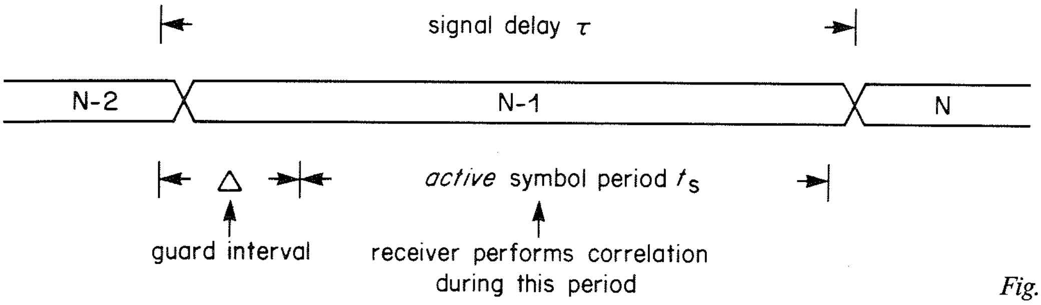
signal delay τ
N-2
N-1
N
Δ
active symbol period t_S
guard interval
receiver performs correlation during this period

Fig. A3.2(a)

In this case the signal is delayed so much that the receiver 'sees' only information belonging to symbol N-1 from the delayed path. If it is simultaneously receiving a direct (or little-delayed) path whose signal contains symbol N then the effect of the delayed path is *totally destructive.*

Reception of signals delayed by τ, where $\Delta < \tau < T_S$:

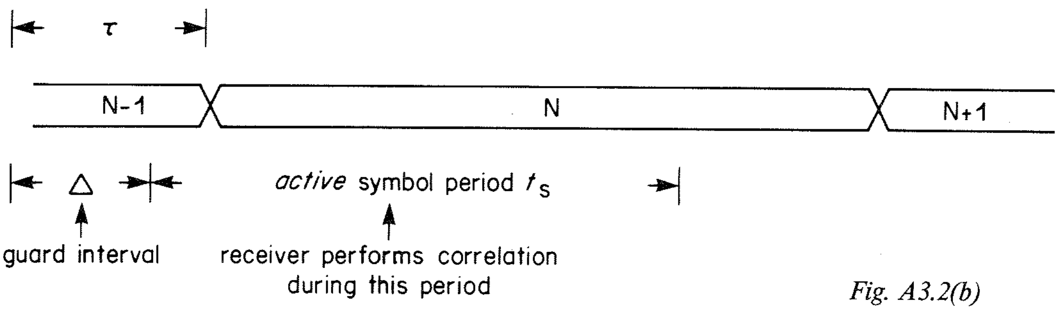
τ
N-1
N
N+1
Δ
active symbol period t_S
guard interval
receiver performs correlation during this period

Fig. A3.2(b)

In this case the receiver 'sees' information from both symbols N−1 and N. Inter-symbol interference therefore occurs but with a severity which depends on the relative proportions of *destructive* 'old' (symbol N−1) and *constructive* 'current' (symbol N) information. The relative proportion thus depends on the value of τ. If τ is little greater than Δ the constructive effect outweighs the destructive effect, and it is thus still advantageous to add a delayed signal to the direct signal. As τ approaches T_S the destructive effect totally dominates and echoes of this delay are thus entirely unwanted.

There is thus a cross-fade from a constructive to a destructive effect of delayed signals as the delay τ increases from Δ towards T_S. Whether the addition of a delayed signal improves or degrades the performance depends on the prevailing instantaneous carrier-to-noise ratio (C/N). For $C/N = 10$ dB, and assuming $\Delta = t_S/4$ (as in the system used), the CCETT have shown that the limiting value of τ, beyond which the addition of a delayed path causes degradation, is $\tau_{LIM} \approx 1.18\Delta$.